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Overview of Heavy Ion Fusion Accelerator Research in the U.S.

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Overview of Heavy Ion Fusion Accelerator Research in the U. S.*

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Abstract. This article provides an overview of current U.S. research on accelerators for Heavy Ion Fusion, that is, inertial fusion driven by intense beams of heavy ions with the goal of energy production. The concept, beam requirements, approach, and major issues are introduced. An overview of a number of new experiments is presented. These include: the High Current Experiment now underway at Lawrence Berkeley National Laboratory; studies of advanced injectors (and in particular an approach based on the merging of multiple beamlets), being investigated experimentally at Lawrence Livermore National Laboratory); the Neutralized (chamber) Transport Experiment being assembled at Lawrence Berkeley National Laboratory; and smaller experiments at the University of Maryland and at Princeton Plasma Physics Laboratory. The comprehensive program of beam simulations and theory is outlined. Finally, prospects and plans for further development of this promising approach to fusion energy are discussed.

INTRODUCTION

A power plant based on Inertial Fusion Energy (IFE) consists of the driver which provides short bursts of energy to be delivered to the targets, the final optical system, the fusion chamber, the targets (along with the factory which produces them), and the generating plant which converts the generated heat into electric power, as shown schematically in Fig. 1. In Heavy Ion Fusion (HIF), intense beams of heavy ions (singly charged, with masses in the range 100-200 AMU) will be accelerated to multi-GeV kinetic energies (several megaJoules total), temporally compressed, and focused onto a

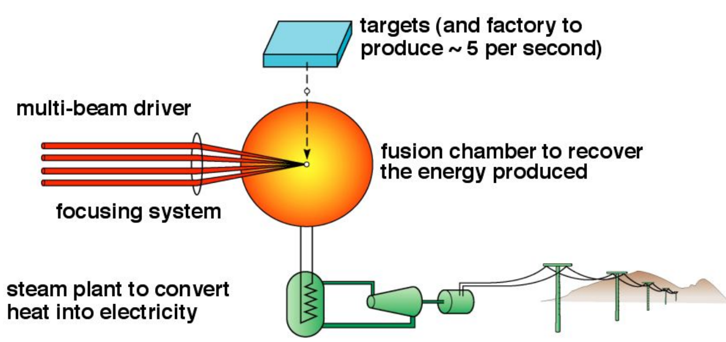

FIGURE 1. Elements of an inertial fusion power plant driven by beams of heavy ions.

target containing fusion fuel, the sequence repeating at about five Hz. Heavy ion beams are attractive for IFE because they can be produced efficiently, and because the final focusing onto the target is achieved by magnetic lenses which can be made robust to the effects of the target explosions. The US HIF program is developing induction accelerators as inertial-fusion drivers both because they can handle much higher currents than radio-frequency (rf) accelerators and because they can amplify those currents, thereby obviating any need for storage rings. Also, induction accelerators were deemed to have a more attractive development path than rf accelerators because most of the key physics issues can be resolved at low energies, allowing them to be studied on small-scale experiments. A schematic of such an induction driver is shown in Fig. 2.

Each fusion target contains a spherical capsule of deuterium-tritium fuel. In the main-line "indirect-drive" option, the ion beams deposit their energy into "radiators" within the target, producing X-rays. The outer layers of the capsule are heated and ablated away by the X-rays; the reaction to this "rocket exhaust" compresses and heats the fuel to a point where fusion ignition and "burn" occur. A number of target concepts appear viable, in particular the "distributed radiator" and "hybrid" targets recently developed at LLNL [1]. A "direct drive" option, wherein the ablation is driven directly by the ion beams, may also be possible.

Because most target concepts require illumination by multiple beams, and because it appears to be expensive to transport the required total current in one or a few beams, a sizable number of beams (of order 100) are confined separately by alternating-gradient quadrupole lenses while accelerated in parallel through a series of toroidal ferromagnetic cores, as shown in Fig. 3. Effectively, the beams act as the secondary "winding" of a series of transformers. The inductive accelerating field across each accelerating gap does not appear on the outside of the structure, and indeed persists until the magnetic field in the core is saturated (a main figure of merit of a core is its Volt-seconds capacity). In some concepts the accelerator employs electrostatic quadrupoles at low energy, but for most of the driver superconducting magnetic "quad" arrays are employed. Longitudinal confinement of the beam tips is effected by shaping the ends of the accelerating waveforms, using so-called "ear" pulses. Induction accelerators are non-resonant and allow the applied voltage waveforms to be tailored as necessary to accelerate, compress, and confine the beams.

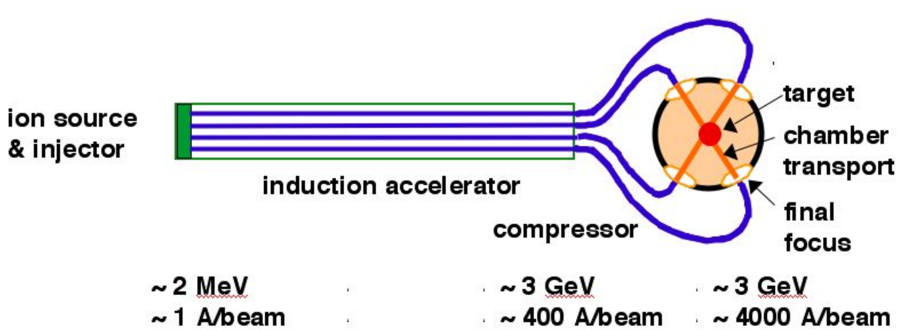

FIGURE 2. Schematic of a Heavy Ion Fusion driver; beam parameters are representative.

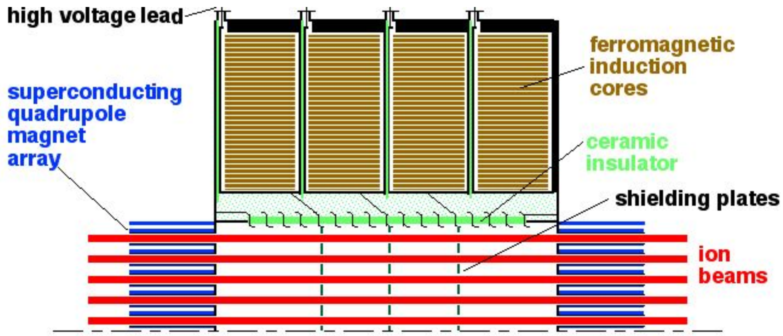

FIGURE 3. Schematic of an accelerating module in high-energy section of a driver.

The intense ion beams are nearly-collisionless nonneutral plasmas and exhibit collective, nonlinear dynamics. They are "space-charge-dominated" — the transverse pressure balance is predominantly between applied focusing (confining) forces and space charge repulsion, with thermal pressure (both transverse and longitudinal) rather smaller in comparison. However, it is the transverse emittance which determines the spot size on target. This emittance represents the area of an ellipse enclosing a fixed large fraction of the beam in a projection such as (x,x') of the full phase space; here x is a transverse coordinate and x' the corresponding momentum normalized to the longitudinal momentum. Also, the pulse must be of the correct duration with minimal longitudinal thermal spread, so that all aspects of the 6-dimensional phase space must be controlled.

Most target concepts require a long "foot" pulse to begin heating the converters and driving the capsule implosion, followed by a shorter "main" pulse of order 10 ns in duration. At present, these pulses are envisioned as traveling down separate beam lines and through separate focusing lenses; this is especially desired when the foot and main pulses are of different kinetic energy, as in recent designs [1]. However, it is also possible to shape the temporal current profile of the individual beams by means of careful manipulations, and indeed some combination of these methods may prove optimal. In any case, acceleration is most efficient when the voltage pulses are of order 100 ns or longer. Thus, toward the end of the accelerator an energy "tilt" is applied to the beams so that their tails are moving faster than their heads as they enter a "drift compression" section. By this means the beams are compressed by a factor of 10–25. The process is arranged so that longitudinal space-charge forces ultimately halt the inward (in the beam frame) compression just as the beams pass through the final focusing optical system. Minimizing the coherent part of the velocity spread in this way reduces the effect of chromatic aberrations on the focal spot. The remaining incoherent thermal spread remains a factor; its influence on the spot size may be reducible by means of additional optical elements, an area of study.

In the fusion chamber, a major consideration is the protection of the walls (and of the final focusing elements) from the neutrons, γ-radiation, and debris produced by the target explosions. An attractive approach is the use of neutronically-thick liquid in the chamber, both for shielding of the "first wall" and as a working fluid which captures the energy produced by the targets and breeds the tritium required for the targets. Sheets, jets, and helical flows (protecting the final sections of the beam tubes) of liquid salts, such as FLiBe (flourine, lithium, and beryllium), are arranged so that the beams can reach the target. The vapor of these compounds, when ionized, can help neutralize the beam; but beam stripping to high charge state (also due to this vapor) requires that the neutralization be nearly complete. X-rays coming from the heated target ionize the vapor and so aid the focusing of the main pulse, but some imperfection in focusing the early parts of the foot pulse may be inevitable [2]. Also of concern are possible beam-plasma instabilities, which so far do not appear sufficiently strong to deflect the beams excessively but merit further study.

Some important issues for HIF drivers are:

Aperture limits: raising the average current density by increasing the fill factor would reduce the size and cost of induction cores, but may exacerbate emittance growth, "halo" ion losses, and ingress of electrons and desorbed gas from the walls. The halo is the small population of particles extending beyond the main, or "core," distribution.

Beam perveance and neutralization limits to final focus and chamber transport: Simulations show that beam neutralization via electrons provided by preformed plasma near the chamber entrance can greatly reduce the net beam space charge and thus allow the use of beams with higher current and lower kinetic energy, reducing driver cost. However, higher beam perveance (roughly, the ratio of the space charge potential to the beam kinetic energy) at final focus can also increase focusing aberrations, and nonlinear residual space charge fields can lead to emittance growth during chamber propagation.

Ion source/injector current density vs. emittance limits for beam arrays: Multiple-beam drivers need compact, high current ion sources. However, a large total current implies a large diode voltage, and breakdown limits imply that the sustainable voltage scales as the square root of the diode gap length. Thus, a high-current single-beam source is necessarily large. We are studying a route to high current based on using multiple apertures per beam, merging many small high-current-density beamlets which may be produced by plasma sources.

Longitudinal drift compression limits: Increasing the velocity "tilt" amplifies the beam peak power, but also multiplies the momentum spread and potentially increases chromatic focusing aberrations. The larger the ratio of initial to final bunch length, the greater the precision in accelerating waveforms that is required.

Multiple beam effects: Inter-beam interactions may be significant toward the end of the driver where most of the axial length is devoted to accelerating gaps, and in the plasma-filled fusion chamber. Transverse electrostatic forces in the gaps can be minimized by inserting shorting plates (with beam holes) in the gaps. Transverse magnetic and longitudinal inductive forces are normally smaller than electric forces, even at the end of the driver, by a factor of $\beta^2 \leq 0.1$, but increase with the number of beams; shielding and longitudinally-offset gaps on the individual beams should reduce these effects.

Cost and performance of essential linac accelerator components: There are many opportunities to improve accelerator technology to reduce the cost of a power plant driver, and of the intermediate facilities that will be required to develop a driver.

These are largely issues of economics rather than of basic feasibility. For example, emittance growth and halo ion losses may be reduced with larger clearance between the beam and the walls, at the expense of quadrupole magnet and induction core sizes. Nonetheless, economic issues are themselves feasibility issues since HIF must compete against other approaches to long-term energy supply.

HIF accelerator development effort in the U.S. is centered in the Virtual National Laboratory for Heavy-Ion Fusion (HIF-VNL), a collaboration which presently involves Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and the Princeton Plasma Physics Laboratory (PPPL). In addition, coordinated research at the University of Maryland, Mission Research Corporation, Stanford Linear Accelerator Center, Sandia National Laboratories, and elsewhere plays an important role. Other institutions are involved in research into target fabrication and injection, power-plant systems, fusion chamber dynamics, and other aspects of HIF. U.S. research also is coordinated with programs carrying out research on related topics at GSI in Germany; at the Institute for Theoretical and Experimental Physics in Russia; at Orsay in France; at RIKEN, Tokyo Institute of Technology, ILE Osaka, and Utsunomia University in Japan, and elsewhere. The reader is referred to the proceedings of a series of international symposia for information on those programs as well as on U.S. work [3, 4, 5, 6]; see also the Heavy Ion Fusion Virtual National Laboratory's web site [7].

NEW BEAM EXPERIMENTS

Earlier experiments at LBNL and LLNL established the basic feasibility of transporting space-charge-dominated beams stably, and of the various manipulations which may be employed in a driver, including beam pulse compression, combining, focusing, and bending. These experiments used low-current beams with driver-like dimensionless parameters, such as perveance; see [8] and references therein. Two new experiments have single-beam currents of hundreds of mA, similar to those at the low-energy end of a driver. These experiments are a High-Current Experiment (HCX) at LBNL to investigate questions of beam transport, acceleration and steering, and possible stray-electron effects; and a set of injector experiments beginning at LLNL, studying the generation of beams by merging a large number of miniature high-brightness beamlets. Another new experiment, the Neutralized Transport Experiment (NTX) at LBNL, models aspects of beam transport in a fusion chamber. Other new experiments include a space-charge-dominated electron ring under construction at the University of Maryland, and a Paul Trap experiment at PPPL, both intended as analogues of intense ion beams. The development of improved diagnostics, and of advanced technology in anticipation of upcoming experiments, are also important parts of the experimental program.

High Current Experiment (HCX)

The HCX [9] began operation in January of 2002. Its principal goals are to investigate aperture limits for space-charge-dominated beams, including the effects of halo production (as a result of beam envelope mismatch or strongly anharmonic fields) and the trapping in the $\sim$2 kV beam potential of stray electrons from gas interactions or produced at the wall by halo ions [10]. The front end consists of an electrostatic-quadrupole injector which generates a single K^+ beam with energy 1-1.8 MeV and current 0.2-0.6 A [11]. The beam then passes through a "matching" section which compresses it transversely

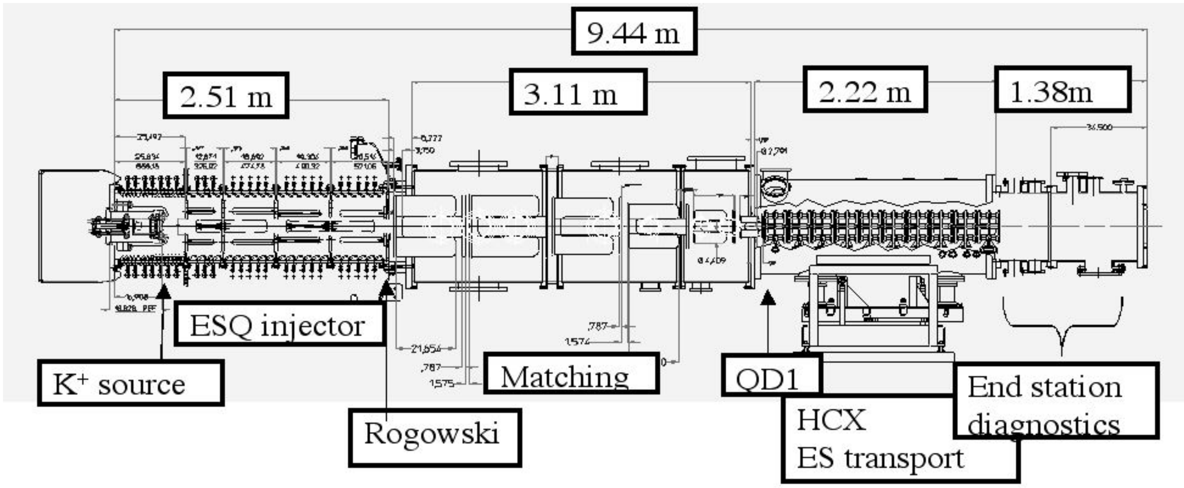

FIGURE 4. High Current Experiment (HCX) layout.

and adjusts its envelope parameters to those needed for the transport line. At present the transport line consists of ten electrostatic quadrupole lenses, each made up of four circular rods surrounding the beam path (Fig. 4). Later this year, four magnetic quads will be added to study, among other things, the trapping of electrons generated by deliberate beam scraping. To allow beam transport over a distance sufficient for significant "relaxation" of the beam distribution, another 20-30 electrostatic quads will be added (simulations show that roughly four to six plasma oscillations are needed). One or more small induction modules will also be added in the magnetic transport section, since the dynamics of trapped electrons are altered significantly by acceleration fields.

The first series of experiments was completed in July of 2002. Much of the effort went into studying a well-matched and -aligned beam. No emittance growth within the sensitivity of the diagnostics, and little or no beam loss, was measured. Faraday cup current traces at the beginning and end of the ten-quad electrostatic transport line are shown in Fig. 5. Preliminary results from the Gas-Electron Source Diagnostic (GESD) were obtained, showing a strong dependence of secondary emission on the angle of incidence as anticipated. Improved diagnostics were deployed, including both parallel and crossed-slit scans to measure multiple projections of the phase space at the beginning and end of the 10-quad transport line. This data is serving as input to a tomographic procedure being developed, with the goal of synthesizing a good estimate of the 4-dimensional transverse phase space that can serve as the initial conditions for particle-in-cell simulations, enabling realistic modeling and detailed comparisons with experiments [12].

Ion Beam Injector Experiments

A new 500-kV ion source test stand, STS-500, shown in Fig. 6, was commissioned in January of 2002. A key mission of this facility will be to investigate an approach to a compact multi-beam injector, whereby each beam is generated by merging a large

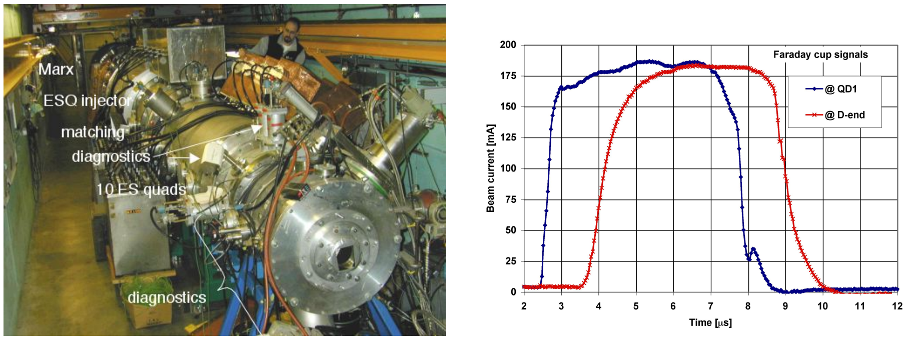

FIGURE 5. HCX in January 2002; Faraday cup traces at transport line entrance and exit.

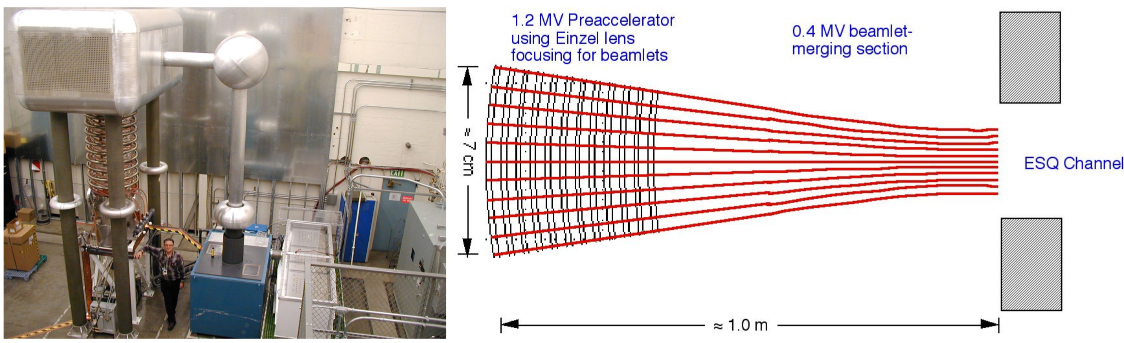

FIGURE 6. Ion source and injector test stand STS-500, and merging-beamlets concept.

number ($\sim$ 100) of small beamlets, each of radius $\sim$ 1-2 mm. As mentioned above, this approach is intended to sidestep the limits on single-beam current density at high current imposed by voltage breakdown considerations. The beamlets are generated in small, bright diodes and may use either plasma sources (being studied on a smaller test stand at LLNL) or hot-plate sources. Downstream of the diodes, further acceleration is effected by an electrostatic aperture column, with Einzel lenses for confinement, as also shown in Fig. 6. In contrast with the large-diameter hot-plate source and ESQ column now in use on HCX, the transverse area requirement of a single-beam injector based on multiple beamlets may be no greater than that of the downstream beam line, enabling a multi-beam system with minimal or no bends in the front end. Furthermore, the array of beamlets may be made elliptical, eliminating the need for a long matching section and the concomitant transverse and longitudinal bulk. Finally, because the beamlets and their associated diodes are small, the pulse rise times may be kept short. The process inevitably entrains empty phase space volume but is calculated to nonetheless yield a beam with sufficient brightness [13]. The ultimate beam produced by such a system can be similar in parameters to the HCX beam, at roughly 0.5 A, 1.6 MeV, and with a normalized emittance of order 1 π-mm-mradian. In addition to the merging process, key issues include the effects on beam quality of background gas pressure, charge exchange, alignment tolerances, and possible beamlet scraping in the aperture columns.

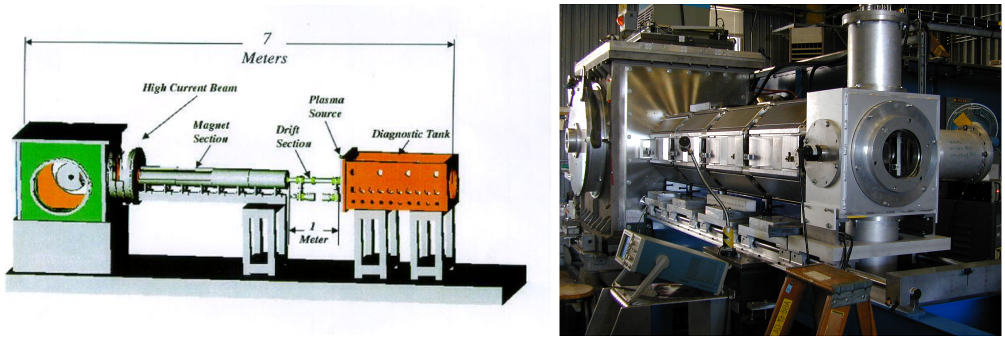

FIGURE 7. Neutralized Transport Experiment (NTX), layout and as of August 2002.

Neutralized Transport Experiment

The NTX began operation in August, 2002. Its principal goals are to investigate the physics of final focusing and chamber transport in the neutralized-ballistic regime, with driver-relevant perveance. The beam is launched by a 300-keV diode. An aperture then trims the beam to a final current of 25-75 mA while electrodes trap secondary electrons. A set of four quadrupole lenses circularize the beam and impart a radially-inward velocity; they can be seen in Fig. 7. Here, studies of chromatic and geometric aberrations, and of means for their minimization, are key goals; the presence of strong space charge is the new element which makes this worthy of study. The experimental plan includes the later addition of octupole lenses to reduce geometric aberrations. Using a pair of plasma sources (the first of which was developed at PPPL) which can be flexibly positioned and actuated, the effects on beam spot size of various methods of neutralization will be assessed. These include a small plasma source at the chamber entrance, and a bulk plasma (such as would be produced by photoionization in a full-scale system) near the nominal focus. The system is designed to have a perveance large enough such that, in the absence of neutralization, the focusing would be poor.

Small Experiments; Diagnostics and Technology Development

The University of Maryland Electron Ring (UMER) is designed to enable studies of beam transport over long path lengths [14]. In this facility, an electron beam with perveance similar to that of a beam in an HIF driver will be injected into a strong-focusing ring and transported around $\sim$10 laps. Induction modules afford longitudinal confinement of the beam by means of "ears," just as in a driver. In the initial configuration the beam will not be accelerated, though this capability may be added later.

The Paul Trap experiment at PPPL [15] is designed to model alternating-gradient focusing using a "beam" that is nearly static and quadrupolar fields which vary in time; this approximates a real system viewed in the beam frame. It is planned that beams will be confined for long times, and the details of the particle distribution function measured.

The moving-slit scanners that have long been used to build up a projection of the phase space over many shots are now being joined by other techniques. The program is making greater use of kapton films on which damage patterns are formed only by ions, eliminating any possibility of confounding by electrons [16]. However, kapton yields only time-integrated data, and so fast-responding scintillators which yield time-resolved data are being developed. By combining such scintillators with upstream slits or hole plates, it should be possible to obtain 3-d or 4-d phase space data instead of just 2-d projections.

Technology development priorities are primarily set by the needs of the experiments, but also look forward to a driver. Recent work has included much progress in the evaluation of low-cost magnetic-core materials and the design of superconducting magnetic-quadrupole arrays. Four prototype quadrupole magnets have been built and tested; a compact cryostated doublet and an optimized prototype quadrupole magnet are being constructed [17]. A long-life alumino-silicate source was developed to replace the older contact-ionization source for HCX, eliminating depletion-induced uncertainties. Work on high-intensity plasma sources has seen initial success, as well.

SIMULATIONS AND THEORY

A central goal of the HIF program is to provide comprehensive simulation and modeling of ion beams, from the source to the target. Simulators and theorists play a major role in guiding the directions of research, support the beam experiments, and develop the improved computational tools needed for future experiments. This effort is divided into roughly 2/3 simulations and 1/3 analytical theory, in four major areas:

<u>Development of the beam physics knowledge base:</u> It is necessary to ensure that no conceptual issues that could impact driver performance remain unexplored. Improved understanding must be distilled into scaling laws and models suitable for inclusion into an accelerator systems code which allows rapid exploration of the parameter space.

<u>Development of the scientific basis for future fusion accelerators,</u> including a full-scale driver and the facilities leading up to it. The emphasis is on synthesis of realizable concepts, and on critical assessment of those concepts.

<u>Studies contributing to the design and interpretation of experiments,</u> including simulations and theoretical analyses of HCX, NTX, injectors, and other experiments.

<u>Development of computational tools.</u> A key goal is a well benchmarked, integrated source-to-target simulation capability that can be used to support the experiments as they develop, and to facilitate the design of future experiments.

For studies of the driver accelerator, our principal tool is a PIC code known as WARP (named for the “warped” coordinates it uses to model a bent beam line). In the fusion chamber, our principal tool is the hybrid implicit electromagnetic PIC code LSP (“Large Scale Plasmas”). Other tools are also used to good advantage. BEST (“Beam Equilibrium, Stability, and Transport”), a nonlinear-perturbative particle code with minimal statistical “noise,” is especially useful for studies of plasma modes. Models which solve the Vlasov equation by advancing the phase space densitiy on a grid, including a Semi-Lagrangian Vlasov package (SLV) now in prototype, are well-suited for studies of low-density beam halo regions which must be minimized for a driver.

Simulations of the HCX ESQ injector were carried out using WARP in a fully 3-d

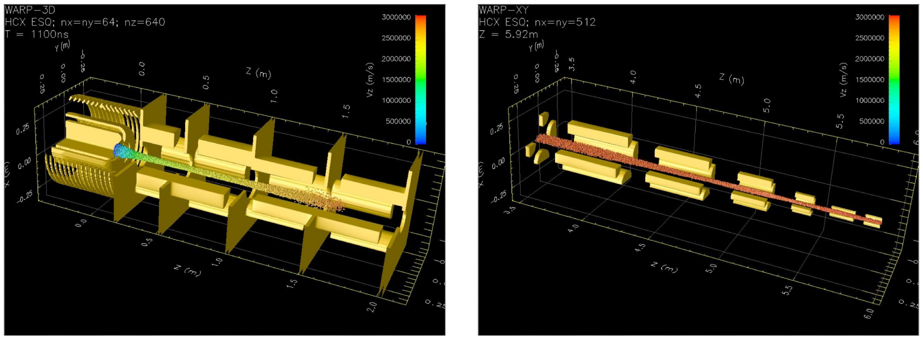

FIGURE 8. WARP simulation of HCX: beam in ESQ and in matching section.

time-dependent mode. The coordinates of particles passing through the exit plane of the ESQ were saved over many time steps during the steady flat-top of the simulated pulse, in order to obtain adequate statistics for a transverse-slice WARPxy simulation of the beam in the matching section and the electrostatic-quadrupole transport line [18]. Frames from a movie generated using the data from such a run are shown in Fig. 8.

The merging-beamlet concept is being simulated in detail [13]. As an example, 91 semi-Gaussian beamlets, each 6 mA with a normalized emittance of 0.003 π-mm-mr), were accelerated across a gap from 1.2-1.6 MeV and followed down the beam line (Fig. 9). The transverse-slice WARPxy simulation used 29 million simulation particles, a 1024×1024 grid, and 4000 time steps, requiring 18.2 hours on 64 processors of the IBM SP computer at the National Energy Research Supercomputer Center.

Simulations of NTX using the LSP code have explored a number of scenarios. In one example, shown in Fig. 10, a plasma near the chamber entrance acts as a source of electrons which are entrained by the K^+ beam as it converges to a focus. In this case the beam is roughly 94% neutralized.

Simulations and theory are also used to explore issues for which there is, as yet, no experiment. These include studies of drift-compression at driver scale, induction-module impedance-driven (resistive wall) instabilities, chamber propagation using the magnetic pinch effect to confine the beams, and other areas. The reader is referred to the Proceedings mentioned above for information [3, 4, 5, 6].

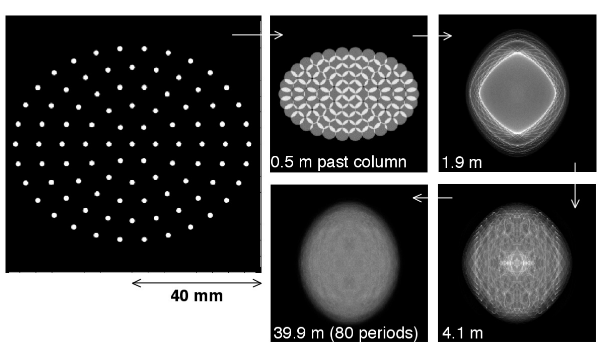

FIGURE 9. Simulation of merging-beamlets process using WARPxy code.

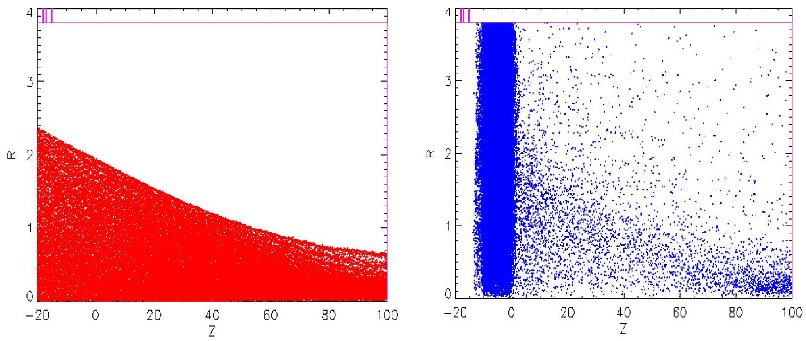

FIGURE 10. LSP simulation of NTX beam in chamber: ions (l) and electrons (r) in r-z plane.

FUTURE STEPS

The current series of experiments is expected to lead to the next step in the HIF driver development path: the Integrated Beam Experiment (IBX), a single-beam induction accelerator which integrates beam injection, electrostatic and magnetic transport, acceleration, steering, and chamber transport in a single machine [19]. The final energy should be of order 10 MeV. Research aimed at developing a compelling physics design for the IBX is underway; there is community-wide agreement on the main goals and rough parameters. IBX will be able to explore most of the key elements of a driver. Key goals include a careful study of longitudinal dynamics, including pulse-end confinement and waves on the beam; halo formation and emittance growth due to any possible slow processes (in general, these effects are expected to occur primarily at transitions along the beam line, where mismatch may be present); chromatic effects in beam bending [20]; and self consistent drift compression, final focusing, and chamber propagation (NTX will not compress the beam, nor allow study of longitudinal dynamics). One of its key missions will be to benchmark and validate the physics understanding and computer simulation tools needed to proceed toward a driver. The principal driver elements not amenable to study on IBX are effects present only at high current with multiple beams, the physics of high energy density in beam-heated matter, and target implosions.

The IBX will provide the physics and technology basis for designing an Integrated Research Experiment (IRE), which could begin construction around 2010. The IRE is intended to test simultaneously all major aspects HIF short of target implosion and burn, including injection, transport in the accelerator, final focusing, transport through a fusion chamber, and beam-target interaction. Together with the target physics database from the laser-based National Ignition Facility, the IRE should provide the scientific and technological basis for an Engineering Test Facility, the final step toward an inertial-fusion demonstration power plant. The reader is referred to [21] for a more complete discussion of program plans.

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